D. Buskulic, I. de Bonis, D. Decamp, P. Ghez, C. Goy, J.P. Lees, A. Lucotte, M.N. Minard, J.Y. Nief, P. Odier, et al.

EUROPEAN LABORATORY FOR PARTICLE PHYSICS

CERN-PPE/96-087
1 July, 1996

Search for Excited Leptons at $130 - 140\,\mathrm{GeV}$

The ALEPH Collaboration

Abstract

A search for the radiative decay of excited charged leptons, ℓ^*, and for radiative and weak decays of excited electron neutrinos, ν_e^*, is performed, using the 5.8 pb^{-1} of data collected by ALEPH at $130 - 140\,\mathrm{GeV}$. No evidence for a signal is found in single or pair production. Excluded mass limits from pair production are close to $65\,\mathrm{GeV}/c^2$ for all excited lepton species. Limits on the couplings, λ/m_{ℓ^*}, of excited leptons are derived from single production. For an excited lepton mass of $130\,\mathrm{GeV}/c^2$, these limits are $0.04\,\mathrm{GeV}^{-1}$ for μ^* and τ^*, and $0.0007\,\mathrm{GeV}^{-1}$ for e^*. For ν_e^*, the limit is at the level of $0.03\,\mathrm{GeV}^{-1}$ for a mass of $120\,\mathrm{GeV}/c^2$, independent of the decay branching ratios.

(To be submitted to Phys. Lett. B)

The ALEPH Collaboration

D. Buskulic, I. De Bonis, D. Decamp, P. Ghez, C. Goy, J.-P. Lees, A. Lucotte, M.-N. Minard, J.-Y. Nief, P. Odier, B. Pietrzyk

Laboratoire de Physique des Particules (LAPP), IN²P³-CNRS, 74019 Annecy-le-Vieux Cedex, France

M.P. Casado, M. Chmeissani, J.M. Crespo, M. Delfino, I. Efthymiopoulos,[20] E. Fernandez, M. Fernandez-Bosman, Ll. Garrido,[15] A. Juste, M. Martinez, S. Orteu, C. Padilla, I.C. Park, A. Pascual, J.A. Perlas, I. Riu, F. Sanchez, F. Teubert

Institut de Fisica d'Altes Energies, Universitat Autonoma de Barcelona, 08193 Bellaterra (Barcelona), Spain[7]

A. Colaleo, D. Creanza, M. de Palma, G. Gelao, M. Girone, G. Iaselli, G. Maggi,[3] M. Maggi, N. Marinelli, S. Nuzzo, A. Ranieri, G. Raso, F. Ruggieri, G. Selvaggi, L. Silvestris, P. Tempesta, G. Zito

Dipartimento di Fisica, INFN Sezione di Bari, 70126 Bari, Italy

X. Huang, J. Lin, Q. Ouyang, T. Wang, Y. Xie, R. Xu, S. Xue, J. Zhang, L. Zhang, W. Zhao

Institute of High-Energy Physics, Academia Sinica, Beijing, The People's Republic of China[8]

R. Alemany, A.O. Bazarko, M. Cattaneo, P. Comas, P. Coyle, H. Drevermann, R.W. Forty, M. Frank, R. Hagelberg, J. Harvey, P. Janot, B. Jost, E. Kneringer, J. Knobloch, I. Lehraus, G. Lutters, E.B. Martin, P. Mato, A. Minten, R. Miquel, Ll.M. Mir,[2] L. Moneta, T. Oest,[1] A. Pacheco, J.-F. Pusztaszeri, F. Ranjard, P. Rensing,[25] L. Rolandi, D. Schlatter, M. Schmelling,[24] M. Schmitt, O. Schneider, W. Tejessy, I.R. Tomalin, A. Venturi, H. Wachsmuth, A. Wagner

European Laboratory for Particle Physics (CERN), 1211 Geneva 23, Switzerland

Z. Ajaltouni, A. Barrès, C. Boyer, A. Falvard, P. Gay, C . Guicheney, P. Henrard, J. Jousset, B. Michel, S. Monteil, J-C. Montret, D. Pallin, P. Perret, F. Podlyski, J. Proriol, P. Rosnet, J.-M. Rossignol

Laboratoire de Physique Corpusculaire, Université Blaise Pascal, IN²P³-CNRS, Clermont-Ferrand, 63177 Aubière, France

T. Fearnley, J.B. Hansen, J.D. Hansen, J.R. Hansen, P.H. Hansen, B.S. Nilsson, B. Rensch, A. Wäänänen

Niels Bohr Institute, 2100 Copenhagen, Denmark[9]

A. Kyriakis, C. Markou, E. Simopoulou, A. Vayaki, K. Zachariadou

Nuclear Research Center Demokritos (NRCD), Athens, Greece

A. Blondel, J.C. Brient, A. Rougé, M. Rumpf, A. Valassi,[6] H. Videau[21]

Laboratoire de Physique Nucléaire et des Hautes Energies, Ecole Polytechnique, IN²P³-CNRS, 91128 Palaiseau Cedex, France

E. Focardi,[21] G. Parrini

Dipartimento di Fisica, Università di Firenze, INFN Sezione di Firenze, 50125 Firenze, Italy

M. Corden, C. Georgiopoulos, D.E. Jaffe

Supercomputer Computations Research Institute, Florida State University, Tallahassee, FL 32306-4052, USA [13,14]

A. Antonelli, G. Bencivenni, G. Bologna,[4] F. Bossi, P. Campana, G. Capon, D. Casper, V. Chiarella, G. Felici, P. Laurelli, G. Mannocchi,[5] F. Murtas, G.P. Murtas, L. Passalacqua, M. Pepe-Altarelli

Laboratori Nazionali dell'INFN (LNF-INFN), 00044 Frascati, Italy

L. Curtis, S.J. Dorris, A.W. Halley, I.G. Knowles, J.G. Lynch, V. O'Shea, C. Raine, P. Reeves, J.M. Scarr, K. Smith, P. Teixeira-Dias, A.S. Thompson, F. Thomson, S. Thorn, R.M. Turnbull

Department of Physics and Astronomy, University of Glasgow, Glasgow G12 8QQ,United Kingdom[10]

U. Becker, C. Geweniger, G. Graefe, P. Hanke, G. Hansper, V. Hepp, E.E. Kluge, A. Putzer, M. Schmidt, J. Sommer, H. Stenzel, K. Tittel, S. Werner, M. Wunsch

Institut für Hochenergiephysik, Universität Heidelberg, 69120 Heidelberg, Fed. Rep. of Germany[16]

D. Abbaneo, R. Beuselinck, D.M. Binnie, W. Cameron, P.J. Dornan, P. Morawitz, A. Moutoussi, J. Nash, J.K. Sedgbeer, A.M. Stacey, M.D. Williams

Department of Physics, Imperial College, London SW7 2BZ, United Kingdom[10]

G. Dissertori, P. Girtler, D. Kuhn, G. Rudolph

Institut für Experimentalphysik, Universität Innsbruck, 6020 Innsbruck, Austria[18]

A.P. Betteridge, C.K. Bowdery, P. Colrain, G. Crawford, A.J. Finch, F. Foster, G. Hughes, T. Sloan, E.P. Whelan, M.I. Williams

Department of Physics, University of Lancaster, Lancaster LA1 4YB, United Kingdom[10]

A. Galla, A.M. Greene, C. Hoffmann, K. Jacobs, K. Kleinknecht, G. Quast, B. Renk, E. Rohne, H.-G. Sander, P. van Gemmeren C. Zeitnitz

Institut für Physik, Universität Mainz, 55099 Mainz, Fed. Rep. of Germany[16]

J.J. Aubert,[21] A.M. Bencheikh, C. Benchouk, A. Bonissent, G. Bujosa, D. Calvet, J. Carr, C. Diaconu, N. Konstantinidis, P. Payre, D. Rousseau, M. Talby, A. Sadouki, M. Thulasidas, A. Tilquin, K. Trabelsi

Centre de Physique des Particules, Faculté des Sciences de Luminy, IN^{2}P^3-CNRS, 13288 Marseille, France

M. Aleppo, F. Ragusa[21]

Dipartimento di Fisica, Universitá di Milano e INFN Sezione di Milano, 20133 Milano, Italy.

C. Bauer, R. Berlich, W. Blum, V. Büscher, H. Dietl, F. Dydak,[21] G. Ganis, C. Gotzhein, H. Kroha, G. Lütjens, G. Lutz, W. Männer, H.-G. Moser, R. Richter, A. Rosado-Schlosser, S. Schael, R. Settles, H. Seywerd, R. St. Denis, H. Stenzel, W. Wiedenmann, G. Wolf

Max-Planck-Institut für Physik, Werner-Heisenberg-Institut, 80805 München, Fed. Rep. of Germany[16]

J. Boucrot, O. Callot, A. Cordier, M. Davier, L. Duflot, J.-F. Grivaz, Ph. Heusse, A. Höcker, A. Jacholkowska, M. Jacquet, D.W. Kim,[19] F. Le Diberder, J. Lefrançois, A.-M. Lutz, I. Nikolic, H.J. Park,[19] M.-H. Schune, S. Simion, J.-J. Veillet, I. Videau, D. Zerwas

Laboratoire de l'Accélérateur Linéaire, Université de Paris-Sud, IN^{2}P^3-CNRS, 91405 Orsay Cedex, France

P. Azzurri, G. Bagliesi, G. Batignani, S. Bettarini, C. Bozzi, G. Calderini, M. Carpinelli, M.A. Ciocci, V. Ciulli, R. Dell'Orso, R. Fantechi, I. Ferrante, A. Giassi, A. Gregorio, F. Ligabue, A. Lusiani, P.S. Marrocchesi, A. Messineo, F. Palla, G. Rizzo, G. Sanguinetti, A. Sciabà, P. Spagnolo, J. Steinberger, R. Tenchini, G. Tonelli,[26] C. Vannini, P.G. Verdini, J. Walsh

Dipartimento di Fisica dell'Università, INFN Sezione di Pisa, e Scuola Normale Superiore, 56010 Pisa, Italy

G.A. Blair, L.M. Bryant, F. Cerutti, J.T. Chambers, Y. Gao, M.G. Green, T. Medcalf, P. Perrodo, J.A. Strong, J.H. von Wimmersperg-Toeller

Department of Physics, Royal Holloway & Bedford New College, University of London, Surrey TW20 OEX, United Kingdom[10]

D.R. Botterill, R.W. Clifft, T.R. Edgecock, S. Haywood, P. Maley, P.R. Norton, J.C. Thompson, A.E. Wright

Particle Physics Dept., Rutherford Appleton Laboratory, Chilton, Didcot, Oxon OX11 OQX, United Kingdom[10]

B. Bloch-Devaux, P. Colas, S. Emery, W. Kozanecki, E. Lançon, M.C. Lemaire, E. Locci, B. Marx, P. Perez, J. Rander, J.-F. Renardy, A. Roussarie, J.-P. Schuller, J. Schwindling, A. Trabelsi, B. Vallage

CEA, DAPNIA/Service de Physique des Particules, CE-Saclay, 91191 Gif-sur-Yvette Cedex, France[17]

S.N. Black, J.H. Dann, R.P. Johnson, H.Y. Kim, A.M. Litke, M.A. McNeil, G. Taylor

Institute for Particle Physics, University of California at Santa Cruz, Santa Cruz, CA 95064, USA[22]

C.N. Booth, R. Boswell, C.A.J. Brew, S. Cartwright, F. Combley, A. Koksal, M. Letho, W.M. Newton, J. Reeve, L.F. Thompson

Department of Physics, University of Sheffield, Sheffield S3 7RH, United Kingdom[10]

A. Böhrer, S. Brandt, G. Cowan, C. Grupen, P. Saraiva, L. Smolik, F. Stephan,
Fachbereich Physik, Universität Siegen, 57068 Siegen, Fed. Rep. of Germany[16]

M. Apollonio, L. Bosisio, R. Della Marina, G. Giannini, B. Gobbo, G. Musolino
Dipartimento di Fisica, Università di Trieste e INFN Sezione di Trieste, 34127 Trieste, Italy

J. Putz, J. Rothberg, S. Wasserbaech, R.W. Williams
Experimental Elementary Particle Physics, University of Washington, WA 98195 Seattle, U.S.A.

S.R. Armstrong, P. Elmer, Z. Feng,[12] D.P.S. Ferguson, Y.S. Gao,[23] S. González, J. Grahl, T.C. Greening, O.J. Hayes, H. Hu, P.A. McNamara III, J.M. Nachtman, W. Orejudos, Y.B. Pan, Y. Saadi, I.J. Scott, A.M. Walsh,[27] Sau Lan Wu, X. Wu, J.M. Yamartino, M. Zheng, G. Zobernig
Department of Physics, University of Wisconsin, Madison, WI 53706, USA[11]

---

[1]Now at DESY, Hamburg, Germany.
[2]Supported by Dirección General de Investigación Científica y Técnica, Spain.
[3]Now at Dipartimento di Fisica, Università di Lecce, 73100 Lecce, Italy.
[4]Also Istituto di Fisica Generale, Università di Torino, Torino, Italy.
[5]Also Istituto di Cosmo-Geofisica del C.N.R., Torino, Italy.
[6]Supported by the Commission of the European Communities, contract ERBCHBICT941234.
[7]Supported by CICYT, Spain.
[8]Supported by the National Science Foundation of China.
[9]Supported by the Danish Natural Science Research Council.
[10]Supported by the UK Particle Physics and Astronomy Research Council.
[11]Supported by the US Department of Energy, grant DE-FG0295-ER40896.
[12]Now at The Johns Hopkins University, Baltimore, MD 21218, U.S.A.
[13]Supported by the US Department of Energy, contract DE-FG05-92ER40742.
[14]Supported by the US Department of Energy, contract DE-FC05-85ER250000.
[15]Permanent address: Universitat de Barcelona, 08208 Barcelona, Spain.
[16]Supported by the Bundesministerium für Forschung und Technologie, Fed. Rep. of Germany.
[17]Supported by the Direction des Sciences de la Matière, C.E.A.
[18]Supported by Fonds zur Förderung der wissenschaftlichen Forschung, Austria.
[19]Permanent address: Kangnung National University, Kangnung, Korea.
[20]Now at CERN, 1211 Geneva 23, Switzerland.
[21]Also at CERN, 1211 Geneva 23, Switzerland.
[22]Supported by the US Department of Energy, grant DE-FG03-92ER40689.
[23]Now at Harvard University, Cambridge, MA 02138, U.S.A.
[24]Now at Max-Plank-Institüt für Kernphysik, Heidelberg, Germany.
[25]Now at Dragon Systems, Newton, MA 02160, U.S.A.
[26]Also at Istituto di Matematica e Fisica, Università di Sassari, Sassari, Italy.
[27]Now at Rutgers University, Piscataway, NJ 08855-0849, U.S.A.

1 Introduction

Excited leptons are natural corollaries of models where the standard leptons are composite rather than elementary particles [1]. The mass gap to the first excited level is determined by the compositeness scale and, if not too large, may be bridged by the LEP energy. In this study, only spin 1/2 and isospin 0 or 1/2 excited leptons, ℓ^*, are considered. (Other cases have been discussed in Ref. [2]). If the excited states acquire mass above the electroweak breaking scale (so as to motivate the rather large mass gap), they have vector-like couplings. The alternative is to assume a chirality structure identical to that of the ground state leptons. As the latter is a more conservative choice, leading to lower production cross-sections, limits will be derived for this particular case.

At LEP, excited leptons can be produced singly ($e^+e^- \rightarrow \ell\ell^*$), or in pairs ($e^+e^- \rightarrow \ell^*\bar{\ell}^*$). For single production, the effective Lagrangian is given [1] by

$$\mathcal{L}_{\text{eff}} = \sum_{V=\gamma,Z,W} \frac{e}{\Lambda} \bar{\ell}^* \sigma^{\mu\nu} (c_{V\ell^*\ell} - d_{V\ell^*\ell}\gamma^5) \ell \partial_\mu V_\nu + h.c.$$

The precision $g-2$ measurements imply $|c_{\gamma\ell^*\ell}| = |d_{\gamma\ell^*\ell}|$ and the absence of electric dipole moments requires $c_{\gamma\ell^*\ell}$ and $d_{\gamma\ell^*\ell}$ to have the same phase [1, 3]. In [1] the couplings all satisfy $c_{V\ell^*\ell} = d_{V\ell^*\ell}$ and can be written:

$$\begin{aligned}
c_{\gamma e^* e} &= -\frac{1}{4}(f + f') \\
c_{\gamma \nu^* \nu} &= \frac{1}{4}(f - f') \\
c_{Z e^* e} &= -\frac{1}{4}(f \cot\theta_W - f' \tan\theta_W) \\
c_{Z \nu^* \nu} &= \frac{1}{4}(f \cot\theta_W + f' \tan\theta_W) \\
c_{W \nu^* e} &= \frac{f}{2\sqrt{2}\sin\theta_W}
\end{aligned}$$

The independent parameters in the model are f/Λ and f'/Λ. By choosing a particular relationship between f and f', λ/m_{ℓ^*}, defined as $f/\sqrt{2}\Lambda$, remains the only free parameter. The scale, Λ need not be the same for the different lepton flavours.

For pair production, couplings of the same form as in the Standard Model are assumed, the contributions from the above magnetic couplings being expected to be much smaller [4]. The possibility of a form-factor [5], multiplying the standard couplings, is also considered.

The presence of magnetic couplings allows the excited leptons to decay to their ground state partners and a vector boson. Branching ratios are calculated according to [5]. For excited charged leptons, $f = f' = 1$ is assumed. For ℓ^* masses below the W and Z, the branching ratio for the radiative decay, $\ell^* \rightarrow \ell\gamma$, is virtually 100%. For larger ℓ^* masses the decay channels involving W and Z open up, and for a 140 GeV/c^2 ℓ^* mass the photonic decay branching ratio is reduced to 43%. The radiative decay of excited neutrinos is only allowed if $f \neq f'$: for the case $f' = 0$ and $f = 1$ the branching ratio for the photonic decay drops to 14% for a 140 GeV/c^2 ℓ^* mass while that of the charged current decay increases to 66%.

All the data taken by the ALEPH detector [6, 7] in the high energy runs in 1995 were used to search for excited leptons. The centre of mass energies were 130.2, 136.3 and 140.0 GeV, with corresponding integrated luminosities of 2.88, 2.87 and 0.05 pb^{-1}.

2 Pair Production of Excited Charged Leptons

Excited charged lepton pair production is dominated by s-channel γ or Z exchange. The production rates are thus similar to those for standard, but heavy, leptons, and the radiative decay modes lead to characteristic topologies, $\ell^+\ell^-\gamma\gamma$. The standard model background from lepton pair production with final state radiation can be efficiently reduced by imposing isolation cuts on the photons. As the pair production cross sections are large, the previous LEP1 limit, 46.2 GeV/c^2, can be improved thanks to the increased centre-of-mass energy, even with modest luminosity.

In all channels henceforth, the default selection cuts require the polar angles of all identified charged tracks and photons to be greater than $18.2°$ and the charged track momenta to be greater than 0.5 GeV/c.

Events with two identified photons with energy exceeding 8.5 GeV and either two or four tracks are selected. In four track events, there must be one τ candidate, defined as a track triplet with an invariant mass below 1.6 GeV/c^2. The photons are required to be isolated from all charged tracks by at least $25°$. In the data there are two two-track events with photons of the required energies, but in both cases one photon fails the track-isolation cut. There is also one event with four tracks and accepted photons, but all possible track-triplets have invariant masses above 2.3 GeV/c^2, so there is no τ-triplet candidate.

Backgrounds were studied using standard electroweak generators, with full detector simulation. In a sample 25 times as large as the data, no background Monte Carlo events survived the full set of cuts. Signal events were generated using the KORALZ [8] program modified to produce $\ell^*\bar{\ell}^*$ pairs decaying radiatively and fully simulated in the ALEPH detector Monte Carlo. Over most of the mass-range $45 - 68$ GeV/c^2, the efficiency is 58% for $\mathrm{e}^*\mathrm{e}^*$, 61% for $\mu^*\mu^*$ and 43% for $\tau^*\tau^*$.

With no events observed, 95% C.L. mass limits are set as shown in fig. 1a. Excited states with masses up to 65.2 GeV/c^2 for e^*, 65.4 GeV/c^2 for μ^*, and 64.8 GeV/c^2 for τ^* are excluded.

Also shown in fig. 1a is the mass limit for ν^* pair-produced *via* Z-exchange and decaying radiatively. Here, the analysis described in [9] was employed: no acoplanar photon pair events were found, against a background estimate of two. The efficiency of that analysis for the fully simulated Monte Carlo signal was found to be 63%, approximately independent of the ν^* mass. The mass limit for a single ν^* flavour is 63.6 GeV/c^2.

For masses below the above limits, the 95% C.L. excluded form-factor limit is shown in fig. 1b.

3 Single Production of Excited Charged Leptons

Excited charged leptons can also be produced singly, in association with their ground state partner. Masses close to the centre-of-mass energy can be probed this way, but the production cross section now involves the magnetic coupling, the magnitude of which is unknown. For all flavours, the production can take place *via* s-channel γ or Z exchange. For excited electrons another production mechanism, the so-called quasi-real Compton scattering, also contributes: an excited electron is produced in the collision of an electron with a quasi-real photon radiated by an incoming positron.

In single production, the final state consists of two leptons and a photon. An analysis of this topology has been performed to search for excited muons and taus. For excited electrons, quasi-real Compton scattering largely dominates the production cross-section. Since the spectator electron remains undetected in the beam pipe, the apparent topology, only one electron and a photon, is different. A dedicated analysis has therefore been performed for excited electrons.

The small amount of luminosity collected at energies well above the Z peak does not allow any improvement to be expected with respect to the LEP1 results for excited lepton masses smaller than $85\,\mathrm{GeV}/c^2$. Therefore, the selection criteria were optimized for larger masses.

3.1 Single Production of Excited Muons and Taus

To qualify, an event has to consist of a dilepton pair (two tracks or one track and a tau-candidate triplet) and one isolated photon of energy above the lower kinematic limit for a signal of mass $85\,\mathrm{GeV}/c^2$. This corresponds to a photon energy of about 27 GeV at 130 GeV centre-of-mass energy. The isolation criterion is the same as in the previous section.

From the charged tracks and the photon, the "visible" event energy, momentum and mass are computed. Events are also reconstructed allowing for an initial state radiation photon along the beam direction. The lepton momenta and the detected photon energy are recalculated imposing energy and momentum conservation [10]. In the tau channel, only the track or triplet directions are used. The energy of the radiative photon is subtracted from the nominal centre-of-mass energy to produce an "effective" event energy (and similarly an effective event momentum and an effective event mass). Subtracting the detected photon energy in addition produces the "expected track energy".

An event is candidate in the muon channel if less than 10% of the expected track energy is detected in the electromagnetic calorimeter, and if at least 85% of the effective event energy is detected. The visible event mass must be consistent with the effective event mass to within $10\,\mathrm{GeV}/c^2$. At least one track must be identified as a muon by the standard ALEPH algorithm [7] and the opening angle of the tracks is required to be greater than 10° and less than 170°.

An event is candidate in the tau channel if less than 75% of the expected track energy is detected in the electromagnetic calorimeter, and if less than 85% of the effective event energy is detected. In addition, the squared missing mass of the event, calculated by comparing the visible and the effective event energies and momenta, is required to be at least 1200 $(\,\mathrm{GeV}/c^2)^2$ (300 in the four-track case).

Finally, the invariant mass of the dilepton system is required to be less than 84 GeV/c^2 or greater than 97 GeV/c^2. This removes a large fraction of the remaining background from the Zγ final state where the on-shell Z has decayed to a lepton pair, as shown in fig. 2.

Signal and background events were fully simulated. The muon and tau backgrounds were studied using the KORALZ generator. About one event is expected in each of the muon and tau channels, while two μ^* and no τ^* candidates were selected in the data. For the signal, the MUSTAR [11] generator was used, with initial state radiation and with tau decays implemented. The efficiencies for μ^* and τ^* are found to be 67% and 38% respectively for most of the mass range. The lower efficiency for the τ^* case is due to the greater difficulty in reconstructing the events, as the τ directions are estimated from those of their decay products.

The invariant mass resolutions, σ, for μ^* and τ^* are 50 MeV/c^2 and 2 GeV/c^2 respectively. Limits for the μ^* and τ^* couplings are shown in fig. 3, calculated using mass bins of width 4σ.

3.2 Single Production of Excited Electrons

The main backgrounds come:

- from radiative Bhabha scattering with one of the final state electrons remaining undetected in the beam pipe;
- from Bhabha scattering with one of the final state electrons transferring practically all of its energy to a photon through hard bremsstrahlung in the detector material;
- from $\gamma\gamma$ final states with one of the photons converting in the detector material into an e^+e^- pair asymmetric enough for one of the electrons to escape detection.

The Monte Carlo generators TEEGG7 [12], UNIBAB [13] and GGG [14] were used to study these backgrounds.

Following the analysis of ref. [10], events are selected containing exactly one track and one photon, with polar angles greater than 25° and photon energy greater than 10 GeV. The beam axis is required to lie within the plane defined by the track and the photon to within 0.4°. The polar angle of the missing momentum, interpreted as the momentum of an escaping electron, is required to be less than 2°. The configuration where the missing particle has a polar angle greater than 2° but a transverse momentum too low to enter the main tracking detector (the TPC) is taken care of by vetoing events with a large number (> 13) of unassociated hits in the inner tracker; this cut also removes most of the events resulting from hard external bremsstrahlung. The total energy in the event, including the calculated energy of the missing electron, is required to be more than 92.5% of the centre-of-mass energy.

The charged track must be identified as an electron by the standard ALEPH identifiers [7], and the sign of its charge must be the same as that of the beam particle whose direction is the same as the boost direction of the system defined by the detected particles. About three events are expected while three e^* candidates were selected in the data.

The signal was fully simulated using the ESTAR [15] generator and the efficiency was found to be 60% for most of the mass range. Using only the polar angles of the 2 detected particles, the resulting mass resolution is $60\,\mathrm{MeV}/c^2$, and the limit is calculated using mass bins $200\,\mathrm{MeV}/c^2$ wide. The resulting exclusion limit is shown in fig. 3.

4 Excited Neutrinos

The largest cross-section for excited neutrino production at these energies is for t-channel ν_e^* production, *via* W-exchange, in association with a standard ν_e.

In the case where $f = f'$, the $\gamma\nu^*\nu$ coupling vanishes and only weak decays are allowed. The signature of charged current decays is missing energy and an electron:

$$\mathrm{e}^+\mathrm{e}^- \rightarrow \nu_e\bar{\nu}_e^* \rightarrow \nu_e \mathrm{eW} \rightarrow \nu_e \mathrm{e} + \left\{ \begin{array}{l} \mathrm{q\overline{q}'} \\ \ell\nu \end{array} \right.$$

The search for charged current decays in the case of leptonic decays of the W was carried out using the acoplanar lepton pair analysis developed for supersymmetric particle searches [16] which is sensitive to the same final state.

For the hadronic W decays a specific analysis was carried out as follows. Leptonic and most $\gamma\gamma$ events are removed by requiring more than eight charged tracks. The total energy seen in the calorimeter within 12° of the beam axis is required to be $< 0.5\,\mathrm{GeV}$ to reduce events incompletely contained in the detector acceptance. The visible energy in the event must be larger than $90\,\mathrm{GeV}$, which removes all remaining $\gamma\gamma$ events. At energies above the Z peak many events contain a hard radiative isolated photon. To remove such background events it is required that the energy in a cone of 10° opening angle around the most energetic photon be greater than $1\,\mathrm{GeV}$. In signal events the W recoils from a neutrino of high momentum, usually within the detector acceptance. Accordingly it is required that the energy in a cone of 10° opening angle around the missing momentum vector be less than $1\,\mathrm{GeV}$, that the polar angle of the missing momentum vector be greater than 23.5° and that the total missing momentum be greater than $10\,\mathrm{GeV}/c$. At least one track must be identified as an electron, with energy greater than $8\,\mathrm{GeV}$. The mass of the system formed by all the other particles in the event is required to be between 60 and $91\,\mathrm{GeV}/c^2$. For the 19% of events containing more than one electron, the condition has to be fulfilled for at least one of them.

The background processes considered were $\mathrm{q\overline{q}}$, $\mathrm{We}\nu$ and Zee, generated using PYTHIA [17], $\gamma\gamma$ events generated using PHOT02 [18] and WW events generated using LPWW02 [19]. After all the cuts, one event is expected and none is observed.

The signal generator is based on [20], with cross-sections calculated as in [1]. All events were fully simulated in the Aleph detector Monte Carlo. The overall signal efficiency, including branching ratios, for ν_e^* masses in the range 92 to $133\,\mathrm{GeV}/c^2$ is approximately 52%, independent of ν^* mass. Limits on the coupling, $\lambda/m_{\nu_e^*}$ as a function of ν_e^* mass for $f = f' = 1$, which forbids the radiative decay, are shown in fig. 4 (solid line).

In the case where $f \neq f'$ the radiative decay of ν_e^* is allowed in addition to the weak decays. The case where $f = 1$ and $f' = 0$ is considered. The characteristic signature is a single energetic photon. For this topology, the analysis follows that of [9] but, in addition, to reduce background from radiative Z production it is required that the photon polar angle should be greater than 38° and that the missing mass recoiling from the photon should be less than $82.5\,\mathrm{GeV}/c^2$. No events remain in the data, with a predicted background of 2; the signal efficiency measured by full Monte Carlo simulation varies from 48% to 64%, increasing with the ν_e^* mass. Fig. 4 shows the 95% C.L. limits for the coupling $\lambda/m_{\nu_e^*}$, from radiative decay (dashed line) and from the weak decay (dotted line), and the combined limit (dot-dashed line). The omission of searches for neutral current decays has been taken into account.

The topology for charged current ν_e^* decays is exactly the same as for t-channel singly produced heavy neutral leptons [20] to which this analysis has therefore also been applied. The 95% C.L. limit on the square of the heavy neutral lepton mixing matrix element, $|\mathrm{U}|^2$, which describes the mixing between the light electron neutrino and the neutral heavy lepton is 0.1 for a $115\,\mathrm{GeV}/c^2$ heavy neutral lepton mass. Due to the limited statistics, the limits on the mixing obtained are less stringent than those inferred [21] from the measurement of the Z invisible width.

5 Conclusion

Excited leptons were searched for in the data collected by ALEPH at $130-140\,\mathrm{GeV}$. No evidence for a signal was found. Excited states are excluded at 95% confidence level for masses up to 65.2, 65.4, 64.8 and $63.6\,\mathrm{GeV}/c^2$ for e^*, μ^*, τ^* and ν^* respectively. For single production, the 95% C.L. exclusion limits on the couplings, λ/m_{ℓ^*}, for an excited lepton mass of $130\,\mathrm{GeV}/c^2$ are $0.04\,\mathrm{GeV}^{-1}$ for μ^* and τ^*, and $0.0007\,\mathrm{GeV}^{-1}$ for e^*. The limit for ν_e^* is at the level of $0.03\,\mathrm{GeV}^{-1}$ for a mass of $120\,\mathrm{GeV}/c^2$, independent of decay branching ratios.

Similar results have been obtained by other LEP collaborations [22].

6 Acknowledgements

It is a pleasure to thank our colleagues from the accelerator divisions for the excellent performance of LEP at these increased energies. Thanks are also due to all the technical personnel of collaborating institutions for their contribution to the success of ALEPH. Those of us from non-member states thank CERN for its hospitality.

References

[1] K. Hagiwara, S. Komamiya and D. Zeppenfeld, Z. Phys. **C29** (1985) 115.

[2] A. Djouadi, Z. Phys. **C63** (1994) 317;
A. Djouadi and G. Azuelos, Z. Phys. **C63** (1994) 327.

[3] F. M. Renard, Phys. Lett. **116B** (1982) 264;
F. de Aguila, A. Mendez and R. Pascual, Phys. Lett. **140B** (1984) 431;
M. Suzuki, Phys. Lett. **143B** (1984) 237.

[4] see for instance Particle Data Group, Phys. Rev. **D50** (1994) 1805.

[5] F. Boudjema, A. Djouadi and J.L. Kneur, Z. Phys. **C57** (1993) 425.

[6] ALEPH Collaboration, D. Decamp *et al.*, Nucl. Instrum. Methods **A294** (1990) 121.

[7] ALEPH Collaboration, D. Buskulic *et al.*, Nucl. Instrum. Methods **A360** (1995) 481.

[8] S. Jadach *et al.*, Comput. Phys. Comm. **79** (1994) 503.

[9] ALEPH Collaboration, D. Buskulic *et al.*, “A study of single and multi-photon production in e^+e^- collisions at centre of mass energies of 130 and 136 GeV”, CERN-PPE/96-53 submitted to Phys. Lett. **B**.

[10] ALEPH Collaboration, D. Decamp *et al.*, Phys. Reports **216** (1992) 1.

[11] F. Berends and P. Daverveldt, Nucl. Phys. **B272** (1986) 31.

[12] D. Karlen, Nucl. Phys. **B289** (1987) 23

[13] H. Anlauf *et al.*, Comput. Phys. Commun. **79** (1994) 466.

[14] F Berends and R Kleiss, Nucl. Phys. **B186** (1981) 22.

[15] M. Martinez, R. Miquel and C. Mana, Z. Phys. **C46** (1990) 637.

[16] ALEPH Collaboration, D. Buskulic *et al.*, “Search for supersymmetric particles in e^+e^- collisions at centre-of-mass energies of 130 and 136 GeV”, Phys. Lett. **B373** (1996) 246.

[17] T. Sjöstrand, Comput. Phys. Commun. **82** (1994) 74.

[18] ALEPH Collaboration, D. Buskulic et al. Phys. Lett. **B313** (1993) 509.

[19] R. Miquel and M. Schmitt, “Four fermion production through resonating boson pairs at LEP2”, CERN-PPE/95-109 submitted to Z. Phys. **C**.

[20] W. Buchmüller and C. Greub, “Heavy Majorana neutrinos in electron-positron and electron-proton collisions”, Nucl. Phys. **B363** (1991) 345.

[21] E. Nardi, E. Roulet and D. Tommasini, “Limits on Neutrino Mixing with New Heavy Particles”, Phys. Lett. **B327** (1994) 319.

[22] L3 Collaboration, M. Acciarri *et al.*, "Search for excited leptons in e^+e^- annihilation at $\sqrt{s} = 130 - 140$ GeV.", Phys. Lett. **B370** (1996) 211;
DELPHI Collaboration, P. Abreu *et al.*, "Study of radiative leptonic events with hard photons and search for excited charged leptons at $\sqrt{s} = 130 - 136$ GeV" CERN-PPE/96-060, submitted to Phys. Lett. **B**.

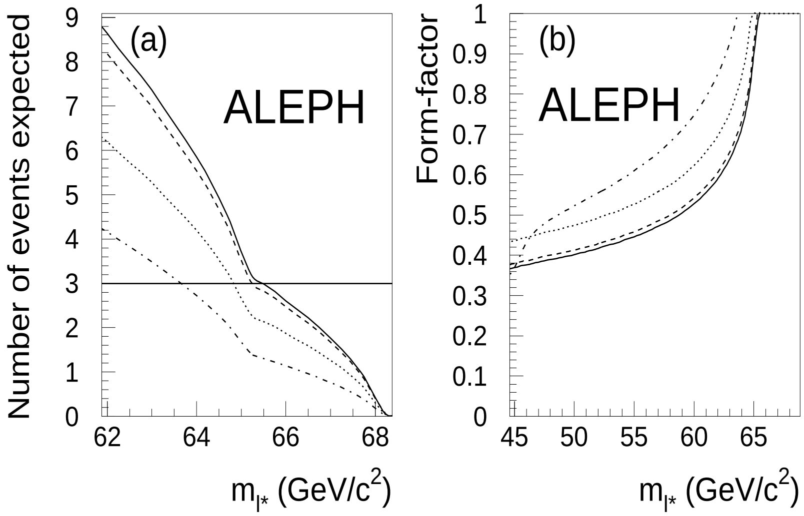

Figure 1: (a) Expected number of $\ell^*\bar{\ell}^*$ events as a function of ℓ^* mass; the excluded mass limits are shown by the horizontal line. (b) the excluded form-factor at 95% C.L. for $\ell^*\bar{\ell}^*$ production as a function of mass. The dashed, solid, dotted and dot-dashed lines denote e^*e^*, $\mu^*\mu^*$, $\tau^*\tau^*$ and $\nu^*\bar{\nu}^*$ respectively in both figures.

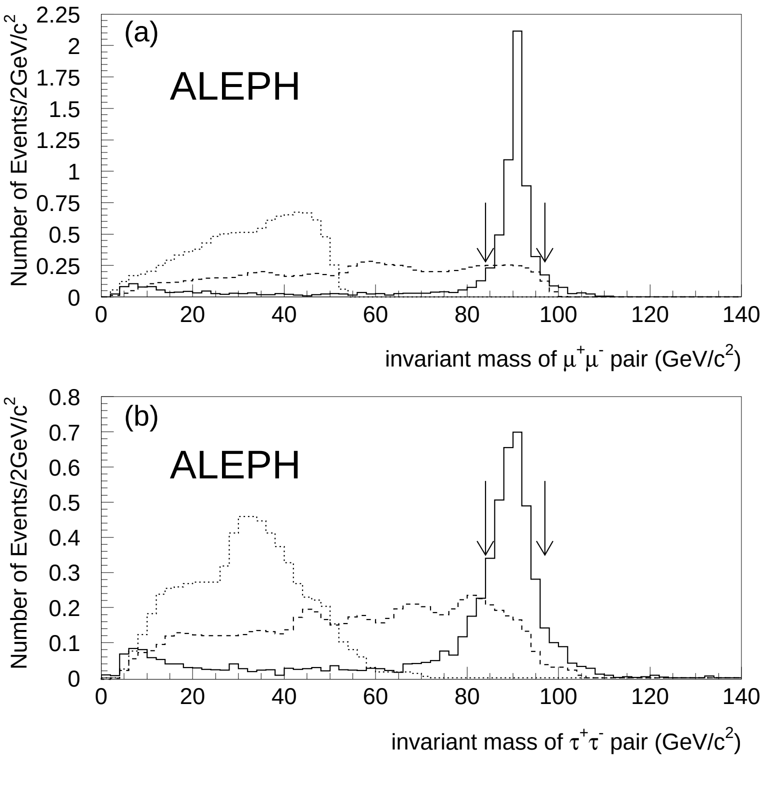

Figure 2: The simulated distribution of the invariant mass of the dilepton system for (a) muon and (b) tau events. The solid line is the background, normalized to the data, and the dashed and dotted lines are signals at 100 and 130 GeV/c^2 respectively. Events with dilepton masses between the arrows are rejected.

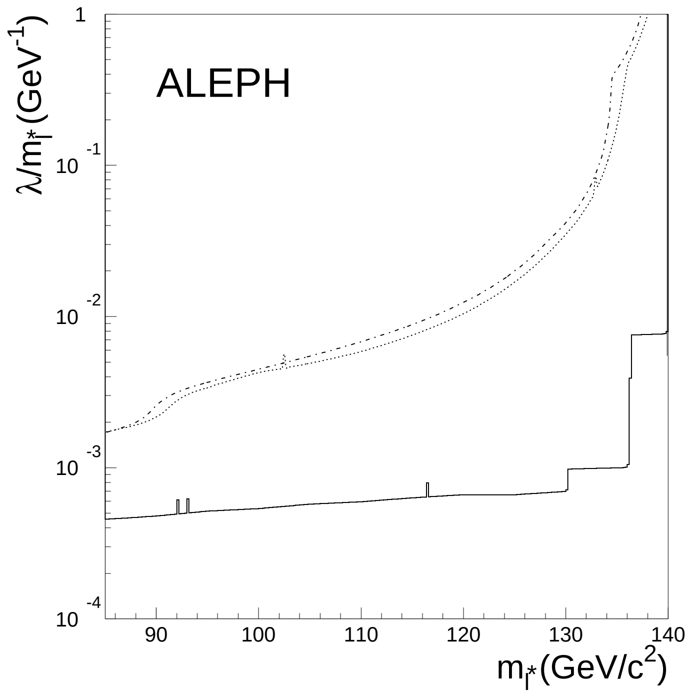

Figure 3: Exclusion limits (95% C.L.) in the mass-coupling plane for singly produced ℓ^*. The vertical ticks on the curves correspond to candidate events. The solid line is the e* limit from quasi-real Compton scattering. The dotted and dot-dashed lines are for μ^* and τ^*, respectively.

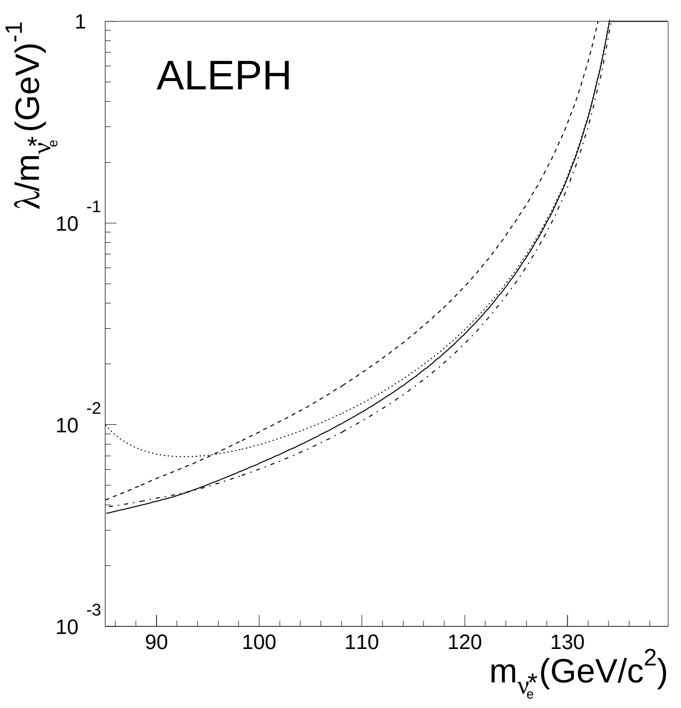

Figure 4: Exclusion limits (95% C.L.) in the mass-coupling plane for singly produced ν_e^* as a function of ν_e^* mass for (i) $f = f' = 1$, (solid line), and (ii) $f = 1$ and $f' = 0$ from radiative decay (dashed line) and from the weak decay (dotted line), and combined limit (dot-dashed line).